

Resolving the gallium anomaly using an opaque liquid scintillator detector

Garv Chauhan^{1,2} and Patrick Huber²

¹*Department of Physics, Arizona State University, 450 E. Tyler Mall, Tempe, Arizona 85287-1504 USA*

²*Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*



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The gallium anomaly has a global significance of greater than 5σ . While SM solutions are not strongly favored, most viable BSM solutions likewise run into strong tensions with reactor and solar neutrino data. In this work, we first emphasize that elastic scattering alone is insufficient to test and resolve the GA. Therefore, we require a detector with a calibrated neutrino source to precisely determine the incoming neutrino energy, avoid radiochemical extraction biases, and isolate oscillation-based effects. We propose to use charged-current neutrino capture on indium (^{115}In) as a target as it offers a low threshold (114 keV) and reasonably high cross section. The triple coincidence provided by ^{115}In neutrino capture can be fully exploited by an opaque scintillation detector that also provides energy and position information. Recent successful research and development by the LiquidO Collaboration makes our proposal realistic and timely. We show that a 100 ton indium target combined with two source runs of a 3.4 MCi ^{51}Cr source can probe the complete parameter space of the gallium anomaly, both in the context of a vanilla sterile neutrino as well as more involved BSM scenarios.

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I. INTRODUCTION

The deficit of event rate induced by monoenergetic neutrinos produced from intense radioactive sources, in gallium-based radiochemical measurements, is commonly termed as the *gallium anomaly* [1–4]. The underlying charged current process is given by

$$\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}. \quad (1)$$

The anomaly currently stands at a global significance of greater than 5σ [5,6]. While there can be possible sources of errors from standard physics, no single factor can explain the anomaly. A simple sterile neutrino explanation runs into strong tension with current solar neutrino bounds, reactor neutrino measurements, and KATRIN data [5,7,8]. For a recent review, see Ref. [6].

The possible standard resolutions include possible errors in source strength determination, neutrino capture cross section on germanium and radiochemical detection efficiency [9,10]. While a combination of these explanations could explain away the anomaly, any one of these reasons by themselves is not sufficient. This might be a clue for the existence of new physics. However, since the

solar and reactor neutrino energies span the same energies as the ^{51}Cr and ^{38}Ar neutrino sources, many elegant solutions quickly run into tension with the solar and reactor data. Some of these explanations, which primarily rely on light sterile neutrinos (ν_s), includes vanilla eV scale ν_s , decaying ν_s , ν_s with *CPT* violation and ν_s coupled to a ultralight scalar [4,7,11–13].

The gallium data to-date has been obtained in radiochemical experiments and hence no information on the event energy or baseline dependence (apart from the 2-zone BEST measurement) is available. We propose a concept where both the baseline and energy can be measured in real time with high accuracy by combining the LENS idea to use ^{115}In as target [14] with a ^{51}Cr radioactive source. The use of indium as a target for low-energy charged-current neutrino detection was first proposed several decades ago as a means to achieve real-time measurements of solar neutrinos [15]. Indium offers a triple coincidence to distinguish neutrino events from intrinsic beta decays of indium. While the concept itself is not new, practical realization has long remained elusive due to limitations in scintillator transparency, light collection, and achievable indium loading. Recent developments in opaque scintillator technology—most notably the LiquidO approach—have revived this idea by offering a feasible path toward constructing detectors with both high indium concentration and sufficient spatial and energy resolution [16–20]. After many years of research and development, the LiquidO Collaboration has demonstrated substantial progress, suggesting that such a

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detector may now finally be within experimental reach. A key advantage of the LiquidO approach is that the detector's performance is not limited by optical transparency, allowing for significantly higher concentrations of indium in the scintillator than would be possible in conventional designs.

However, transitioning from gallium to indium as the target does not eliminate the challenge of accurately determining the neutrino capture cross section. The nuclear physics involved remains complex and in some respects, even more so, since the relevant transition proceeds through an excited state of ^{115}Sn . Since the theoretical prediction of the ^{115}In capture cross section is limited by nuclear-structure uncertainties, the only robust solution is to calibrate it experimentally with a known neutrino flux.

The solar ^7Be line, as originally proposed in the LENS concept, provides a unique opportunity in this regard: it is the only naturally occurring monoenergetic neutrino flux in the relevant energy range and is close in energy to the one from ^{51}Cr , and its interaction rate has been precisely measured by Borexino through neutrino-electron scattering with a precision of 2.6% [21]. This is a purely leptonic process and therefore is calculable from first principles, the ^7Be line can be regarded as a standard candle for the $\nu_e - ^{115}\text{In}$ cross section calibration.

Alternatively, direct measurement of the ^{51}Cr neutrino lines via elastic scattering is experimentally demanding and provides only integrated information on the total flux. In contrast, a charged-current process such as $\nu_e + ^{115}\text{In} \rightarrow ^{115}\text{Sn}^* + e^-$ enables line-resolved detection with precise energy reconstruction. The primary neutrino source in our setup will still be a ^{51}Cr source,¹ but now the low-energy line at 426 keV, whose intensity is known calorimetrically with high precision, can be directly resolved by the detector and used for source-strength calibration. The information about baseline and energy dependence effectively will pin down the underlying physics. Such a measurement becomes feasible when employing a low-threshold charged-current target like ^{115}In , embedded in a scintillation medium with sufficient spatial and energy resolution to reconstruct the event topology in real time, as enabled by the LiquidO concept. As a consequence *all* ingredients can be constrained directly from *data* or well-understood Standard Model physics. Such a measurement, therefore, will close the window on all SM explanations and any deficit will be an unequivocal sign of new physics. This can be achieved, as we will show, with two runs of a 3.4 MCi ^{51}Cr source and a 100 ton indium target in a LiquidO-style detector.

¹The only solar neutrino flux at the ^{51}Cr energy is the carbon-nitrogen-oxygen (CNO) flux, but Borexino has insufficient statistics to effectively test the anomaly; see Appendix A.

II. MSW RESONANCE

Now the focus naturally shifts toward interpreting the anomaly in terms of possible BSM explanations. While the simplest sterile-neutrino hypothesis has long been disfavored by solar, reactor, and kinematic constraints, it remains a useful benchmark. More elaborate oscillation-based models have been proposed but most are in severe tension with existing measurements, as discussed earlier. The specific scenario (proposed in Ref. [10]) we investigate here represents one of the few (perhaps the only) surviving frameworks consistent with all current experimental limits and still viable for the resolution of this anomaly, and the proposed setup would be capable of probing it comprehensively. This solution primarily relies on engineering a fine-tuned MSW/parametric resonance for ν_s through its interactions with ultralight dark matter or dark energy. Such narrow resonances are placed directly at the ^{51}Cr neutrino energies and appearing for only very short baselines of about 1–2 m, hence alleviating any possible tensions from measurement of pp and ^7Be solar neutrino fluxes. We specifically focus on the scenario of ultralight vector dark matter sourcing a potential for ν_s leading to a MSW resonance. Since this case leads to a suppressed effect on the solar neutrino flux compared to the parametric resonance case, this makes our model choice to be conservative. This model can easily evade the solar constraints since the impact is too narrow in energy to be effectively constrained (see Appendix C and Fig. 6 right panel). The sign of the MSW potential ensures that the resonance lies only in the ν sector, while being absent for $\bar{\nu}$'s, thereby, evading $\bar{\nu}$ measurement constraints from reactor and accelerator experiments. The resonance is chosen to lie around the dominant ^{51}Cr neutrino line ~ 747 keV. Therefore, any constraints from high-energy accelerator neutrino measurements ($\gg 747$ keV) can be easily avoided. Finally, the kinematical bounds from KATRIN or $0\nu\beta\beta$ experiments, can be avoided by choosing a small-enough mixing angles for a given vacuum ν_s mass, while suitably choosing a MSW potential V to explain the GA. Therefore, this solution ensures that observable effects only occur for neutrinos at the ^{51}Cr energy (for, e.g., see Fig. 1).

The MSW resonance condition from the presence of ultralight species modifies the probability for detection of electron neutrino for shorter baselines in the following way [10]:

$$P_{ee}^{\text{MSW}}(E_\nu, L) = 1 - \sin^2 2\theta_{e4}^{\text{eff}} \sin^2 \frac{\Delta m_{\text{eff}}^2 L}{4E_\nu}, \quad (2)$$

where $\Delta m_{\text{eff}}^2 = \Delta m^2 (\sin 2\theta_{e4}^{\text{vac}} / \sin 2\theta_{e4}^{\text{eff}})$, where Δm^2 is the vacuum ν_s mass, $\sin 2\theta_{e4}^{\text{vac}}$ is the vacuum mixing angle and the mixing angle in matter $\sin 2\theta_{e4}^{\text{eff}}$ is determined by the interactions of the ν_s with the ultralight dark matter or dark energy,

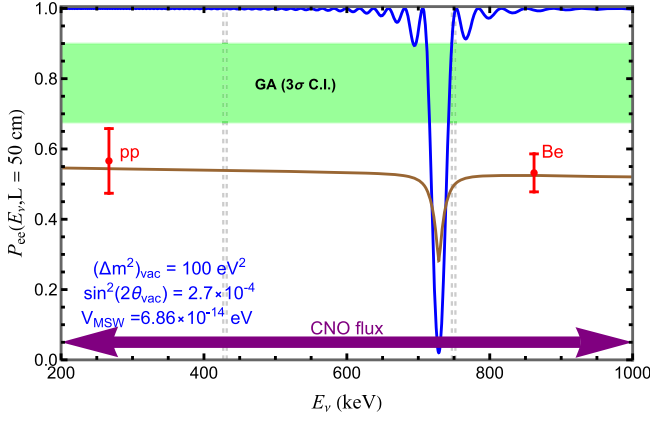


FIG. 1. Electron survival probability P_{ee} with ν_s -DM MSW resonance for a sample point in 95% CI allowed region from all GA experiments (see Fig. 2).

$$\sin 2\theta_{e4}^{\text{eff}} = \frac{\frac{\Delta m_{\text{vac}}^2}{2E_\nu} \sin 2\theta_{e4}^{\text{vac}}}{\sqrt{\left(V - \frac{\Delta m_{\text{vac}}^2}{2E_\nu} \cos 2\theta_{e4}^{\text{vac}}\right)^2 + \left(\frac{\Delta m_{\text{vac}}^2}{2E_\nu} \sin 2\theta_{e4}^{\text{vac}}\right)^2}}, \quad (3)$$

where V is the matter potential difference between ν_e - ν_s . Given the relevant Lagrangian term of the form $-\mathcal{L} \supset g_s \phi^\mu \bar{\nu}_s \gamma_\mu \nu_s$, where g_s is a dimensionless coupling constant, the potential V (solely experienced by ν_s) is generated through interaction of ν_s with the ultralight dark matter ϕ acting as a background medium. We show the 95% CI allowed regions (shaded dark green and labeled

GA) from all GA experiments (SAGE [1], GALLEX [2,3], BEST [4]) for ν_s -DM MSW resonance model in effective (left panel) and vacuum parameter space (right panel) in Fig. 2. The effective parameter values for the left panel have been calculated for $E_\nu \sim 747$ keV, and the dashed blue line denotes the Δm_{eff}^2 value above which the oscillations are averaged out for detector resolution $L_{\text{min}} = 10$ cm. The vacuum parameters for a given set of effective parameters have been determined using definition of Δm_{eff}^2 and Eq. (3). Note that MSW potential V for a given vacuum parameter has not been shown explicitly to enhance clarity, a given set of vacuum parameters $(\Delta m^2, \sin 2\theta_{e4}^{\text{vac}})$ can correspond to multiple values of V that can explain GA. The light green shaded region denotes the region in conflict with the global solar neutrino oscillation data within 1σ ; the gray and blue shaded regions are existing constraint from the neutrinoless double beta decay and KATRIN experiments, respectively. We also note that the best-fit allowed regions for vanilla eV-scale sterile neutrino [4] differ only slightly for our effective parameters best fit at $E_\nu \simeq 747$ keV for MSW resonance case, since due to the absence of any oscillation around the 427 keV ^{51}Cr neutrino line, the required mixing angles to explain the lower Gallium experimental rates are relatively higher. Therefore, the latter best-fit plots shifts slightly to the right.

III. INDIUM DETECTOR

In 1976, Raghavan [15,22,23] put forward a novel proposal to detect the low energy pp-solar neutrinos

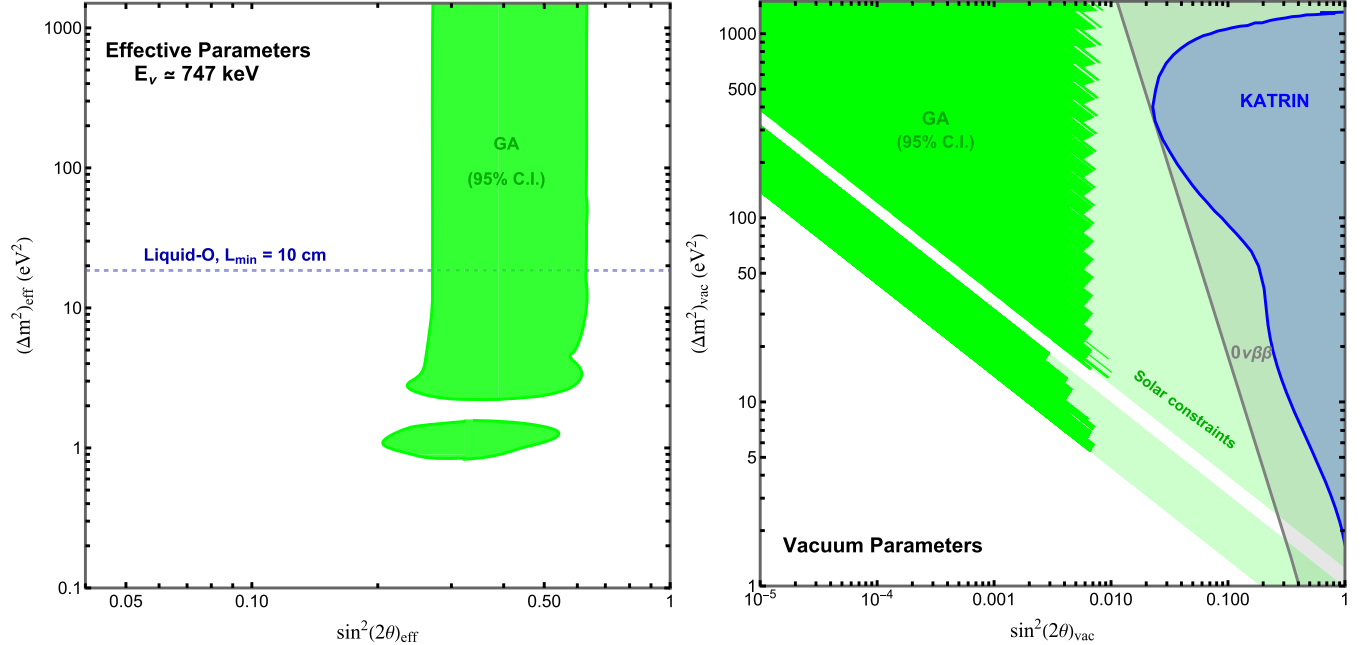


FIG. 2. The best-fit and exclusion contours (95% CI) for the gallium anomaly in effective and vacuum parameter space for ν_s -DM MSW resonance model.

through charged-current driven neutrino capture process on Indium (In),

$$\nu_e + {}^{115}\text{In} \rightarrow {}^{115}\text{Sn}^* + e^-, \quad (4)$$

with a reaction threshold $Q = 114$ keV. The captured neutrino energy E_ν can be reconstructed directly from the final state electron energy $E_e = E_\nu - Q$. The ${}^{115}\text{Sn}^*$ state undergoes delayed deexcitation by emitting two photons of energies 116 keV and 498 keV,

$${}^{115}\text{Sn}^* \rightarrow {}^{115}\text{Sn} + 2\gamma. \quad (5)$$

For future studies, we provide the neutrino capture cross-section on ${}^{115}\text{In}$ [$\sigma_{\text{In}}(E_\nu)$] in Appendix B.

The originally suggested idea was to dissolve (5–10) wt % indium in liquid organic scintillator [15,24,25]. More recently opaque liquid scintillator, that has a shorter scattering than transmission length, has been considered for this application [16,17]. This localizes the light without segmentation and by using wavelength-shifting optical fibers the localized light can be transported over practically arbitrary distances. In such a scheme, a very high indium concentration is possible since light transport happens in the fibers and not in the primary scintillator. This is known as the LiquidO concept [16–18,26] and is a promising technology to use ton-scale indium targets. In the following, we will specify the amount of indium instead of the total detector mass since the actually achievable indium concentration is not yet determined. The lower-energy gamma of the triple coincidence is with 116 keV not an easy target for a detector design with limited photon collection efficiency, achieving a reasonable detection probability for those event probably requires between 10–25 detected photons, or about 100–250 detected photons per MeV of deposited energy. This translates into an energy resolution at the ${}^{51}\text{Cr}$ line of about 80–130 keV. Initial prototypes of the LiquidO technology show promising results [26], and we assume that the required levels of light collection will eventually be reached [16,17]. We furthermore assume that no backgrounds are present, which is plausible since the triple coincidence of the indium reaction precludes accidental backgrounds. The same applies for any backgrounds originating from the ${}^{51}\text{Cr}$ source: the backgrounds from the chromium source are entirely due to impurities in the chromium feed material that get neutron-activated and produce high energy gammas [27], but their rate will be suppressed by the shield to below the one from ${}^{115}\text{In}$ decay.

We do not directly assess the practical engineering challenges of such an indium-doped detector, LiquidO group has argued that the required performance milestones are within reach. The LiquidO prototypes aim to push background levels and light-collection stability to the point where real-time solar neutrino spectroscopy becomes

feasible; achieving those same background-suppression goals for a solar program would render a ${}^{51}\text{Cr}$ source measurement effectively background free. For the purposes of this study, we therefore adopt the conservative working assumption that an experiment built to perform precision solar neutrino measurements could be leveraged (or adapted) to carry out a dedicated test of the gallium anomaly, which has persisted as an outstanding puzzle in neutrino physics for roughly thirty years.

IV. TESTING THE RESONANCE

We will study the sensitivity of the In-doped LiquidO setup to the entire 95% CI best-fit allowed region for the ν_s -DM MSW resonance model, to explain GA. We assume a 3.4 MCi Cr source placed at the center of the detector setup to obtain a high intensity neutrino flux (for schematic diagram, see Appendix C). We assume a data-taking window of approximately 200 days, corresponding to about seven source lifetimes (${}^{51}\text{Cr}$ lifetime is 27.7 days). We estimate the physical size of the neutrino emitting region to be about 10 cm [27], which also is the limit on the shortest wavelength of oscillation that can be resolved. The overall size including the radiation shielding is about ~ 40 cm, which limits how close to the source we can have active detector mass and thus, sharply affects the event rate. Note, that in this geometry, the event rate scales with the detector radius and hence, only with $M_{\text{Ind}}^{1/3}$, *i.e.*, to double the event rate 8 times more indium mass (M_{Ind}) is required. The density of indium in the detector medium also matters since it determines how much indium is within a given distance from the source; we assume 20% indium loading. As expected, for the detection of solar ${}^7\text{Be}$ neutrinos, the event rate is as usual proportional to the total indium mass. Despite the significant thickness of the shielding, there will be residual gamma radiation from neutron-activated trace impurities contained in the source material [9,27]; however, the ${}^{115}\text{In}$ triple coincidence will effectively eliminate this background in particular thanks to the excellent position resolution of the LiquidO technology: high-energy gammas will Compton scatter multiple times and therefore, can be clearly identified. The energies and relative intensities of the four neutrino lines in ${}^{51}\text{Cr}$ decay are 747 keV (81.63%), 752 keV (8.49%), 427 keV (8.95%), and 432 keV (0.93%) [28]. Since in the ν_s -MSW resonance model, we expect a strong suppression for P_{ee} at dominant Cr neutrino line, the difference in the relative intensities and wide energy separation between the ~ 750 keV and ~ 430 keV lines play a crucial role in our analysis. The details of the cross section, event rate and χ^2 calculation can be found in the Appendixes B, C, and D.

The results in Fig. 3 are reported in terms of effective oscillation parameters defined at 747 keV. For the left-hand panel, we assume that there is no external constraint on the $\nu_e - {}^{115}\text{In}$ cross section, that is, the rate is normalized solely

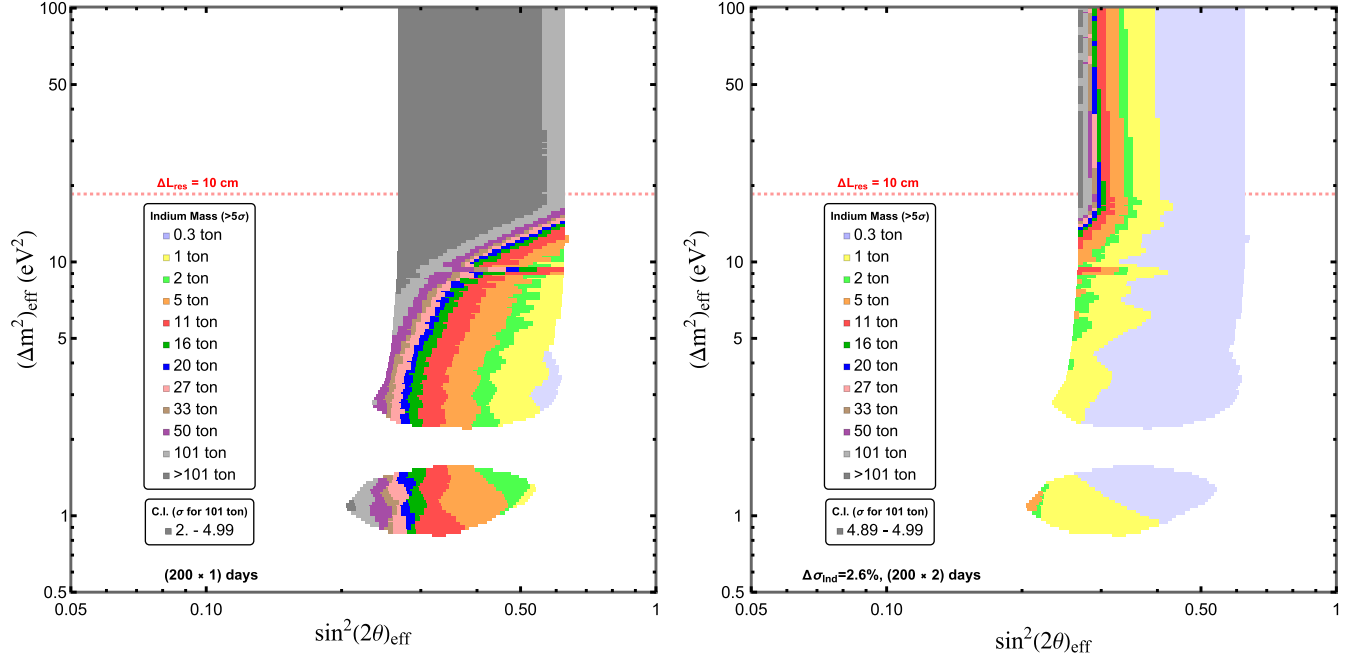


FIG. 3. Plots for sensitivity of the In-doped LiquidO setup. The colored points indicate the required Indium mass to reach confidence interval (CI) of greater than 5σ . All the points shown here are sampled uniformly from the allowed parameter space. The left panel corresponds to single source run with a floating precision on the indium neutrino capture cross section, and a double source run with $\sigma_{\text{In}} = 2.6\%$ in the right panel.

by the 427 keV data. For the right-hand figure, we assume that enough events from ^7Be solar neutrinos have been observed to obtain a statistical uncertainty below 2.6% (the error of the Borexino measurement), and hence, the cross section is constrained to within this value. To reach a statistical precision at this level requires approximately 100 tons of indium target exposed for 10 years. If another measurement of the solar ^7Be flux with higher precision became available, this experiment would become much easier and significantly smaller indium mass would be required, such improvements may come from large liquid noble gas direct dark matter detection experiments [29,30]. We conclude based in the Borexino measurement that even ton-scale experiments can provide useful constraints (at $> 3.5\text{-}\sigma$ level for the entire parameter space) and that a 100 ton experiment can test all of the parameter space at more than $5\text{-}\sigma$ level. None of the proposed measurements rely on radiochemistry or on nuclear matrix elements for inverse beta decay on nuclei.

V. CONCLUSION

The gallium anomaly has been an outstanding problem for about two decades. Resolutions involving vanilla eV-scale sterile neutrino run into strong tensions with solar and reactor measurements. In this work, we have studied tests for a new class of proposed solution based on fine-tuned resonant dips at energies of interest. We propose detecting these low-energy neutrinos through the charged-current

neutrino capture process on ^{115}In . This can be readily realized by doping the opaque liquid organic scintillator experiment proposed by the LiquidO Collaboration. We studied the prospects for such a detector combined with a 3.4 MCi ^{51}Cr neutrino source. We also proposed to use either the 426 keV line from the source or the ^7Be solar neutrino lines to calibrate the neutrino capture cross section. The former case allows to provide stringent tests with ton-scale indium targets only in parts of the parameter space, whereas the latter requires larger detectors up 100 ton indium mass, but can fully probe the parameter space.

Although we have only employed the MSW resonance model to test the sensitivity of the detector setup, many qualitative conclusions for the detector capabilities remain model agnostic and apply to sensitivity reach for other BSM interpretations of the GA anomaly including the vanilla eV-scale ν_s (see Appendix D and Fig. 9 for details) and even exotic decoherence based solution [31].

The advent of Indium-doped LiquidO technology will help unlock new frontiers in sub-MeV neutrino detection by combining precision, scalability, and strong background suppression.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: SOLAR CONSTRAINTS FROM BOREXINO

The BOREXINO experiment has successfully measured multiple components of the solar neutrino flux [21,32,33]. Recently, the result of an improved and final measurement for the CNO ν flux was reported [34–36]. Since the

energies of interest for the GA overlaps with the CNO ν flux, the latest measurement can in principle be used to constrain the features of the MSW resonance. Such a resonance would lead to a sharp dip at the resonant energy in the neutrino flux and thus, affecting the electron recoil spectrum event rate in the detector, which can be calculated as follows [37]:

$$\frac{dR_\nu}{dT} = N_e \int dE_\nu \frac{d\Phi_\nu}{dE_\nu} \left[\frac{d\sigma_e}{dT} P_{ee}(E_\nu) + \left(\cos^2\theta_{23} \frac{d\sigma_\mu}{dT} + \sin^2\theta_{23} \frac{d\sigma_\tau}{dT} \right) (1 - P_{ee}(E_\nu)) \right], \quad (\text{A1})$$

where N_e is the number of e^- in the fiducial volume of the detector, $d\Phi_\nu/dE_\nu$ is the differential neutrino flux spectrum, $P_{ee}(E_\nu)$ is the ν_e survival probability including the resonance effects, $d\sigma_\alpha(E_\nu, T)/dT$ is the differential neutrino-electron scattering cross section with respect to kinetic energy T is given by

$$\frac{d\sigma_\alpha(E_\nu, T)}{dT} = \frac{2}{\pi} G_F^2 m_e \left[g_{\alpha L}^2 + g_{\alpha R}^2 \left(1 - \frac{T}{E_\nu} \right)^2 + g_{\alpha L} g_{\alpha R} \frac{m_e T}{E_\nu^2} \right], \quad \text{where } g_{\alpha L} = -\frac{1}{2} + \sin^2\theta_W + \delta_{\alpha e}, \quad g_{\alpha R} = \sin^2\theta_W, \quad (\text{A2})$$

with maximum recoil energy constrained to be

$$T_{\max} = \frac{E_\nu}{1 + \frac{m_e}{2E_\nu}}. \quad (\text{A3})$$

The electron recoil spectrum in the BOREXINO detector for relevant solar neutrino flux components—pp, pep, CNO, and ^7Be —are shown in Fig. 4. The solid lines denotes the measured recoil spectrum at BOREXINO along with 1σ theoretical uncertainty region shown in shaded purple, while the dotted line shows the modified recoil spectrum in presence of a resonant dip with $E_{\nu, \text{res}} = 750$ keV, $P_{ee}(E_{\nu, \text{res}}) \sim 0.23$ (including solar oscillation effects) and resonance width $\sigma_{\text{res}} \simeq 50$ keV. It can be clearly seen that the electron recoil spectrum cannot uniquely resolve the resonant dip in the CNO neutrino spectrum. The dip appears as a modified shoulder for T_e below 560 keV (corresponding to $T_{\max}$ for $E_{\nu, \text{res}} = 750$ keV). For comparison, the benchmark point chosen by authors in Ref. [10] corresponds to $E_{\nu, \text{res}} = 750$ keV, $P_{ee}(E_{\nu, \text{res}}) \sim 0.28$, and $\sigma_{\text{res}} \simeq 5$ keV. Since it is harder to resolve the sharp dip in the recoil spectrum even for a wider resonance width; therefore, it is not possible to test the viable parameter space for GA only through neutral scattering measurements. For this purpose, we argue for the need for a detector that can measure neutrino interactions through charged current reactions, to resolve the spectral features of the resonant dip and shed light on the nature of explanation that underlies gallium anomaly.

We also note that the measured CNO interaction rate is slightly higher than predicted in the high-metallicity standard solar model (but still within 2σ CI) [38]. This might already disfavor resonant dips, but since the measured rate by BOREXINO depends on the standard CNO spectral shape, this requires further work which is outside the scope of the current study.

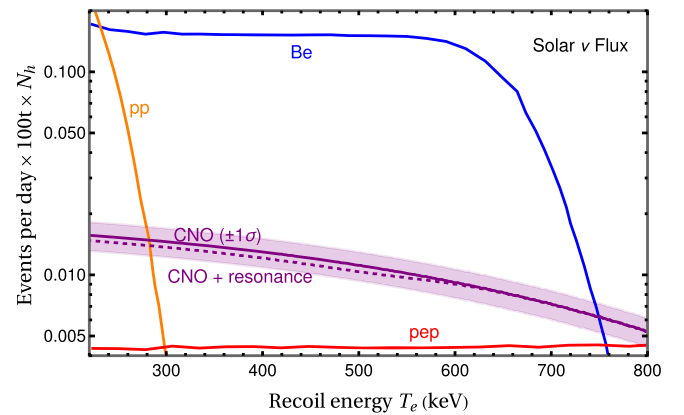


FIG. 4. Electron recoil spectrum for various solar neutrino fluxes— ^7Be , pp, pep, and, CNO with and without the resonance in BOREXINO. The standard expected CNO events are shown by solid purple line with 1σ theoretical uncertainty region shown in shaded purple. The expected spectrum for a resonant 30% dip centered at 750 keV with width 50 keV, is shown by dashed purple line.

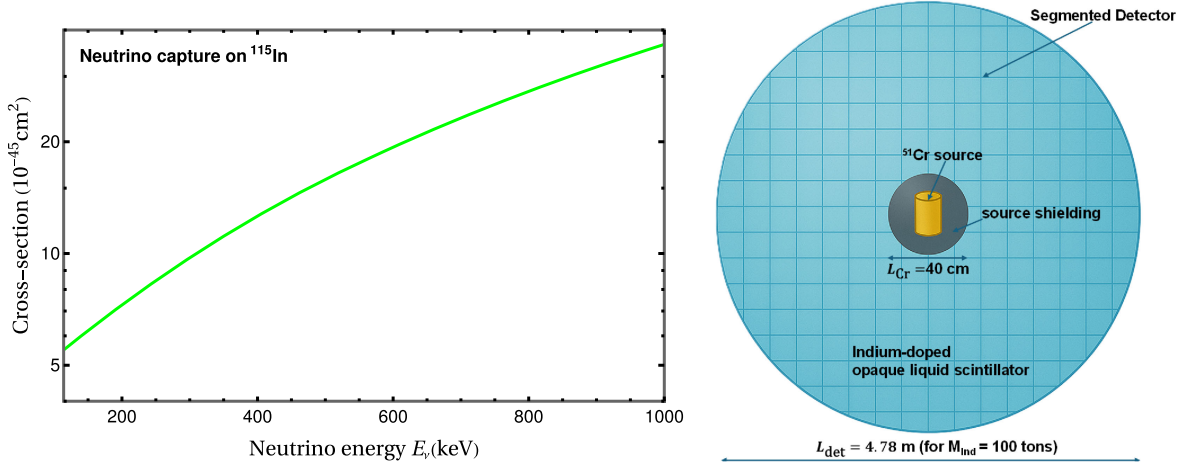


FIG. 5. (Left panel) The cross section for neutrino capture on ^{115}In (in units of 10^{-45} cm^2) as a function of neutrino energy E_ν (in keV). (Right panel) A schematic diagram for a segmented opaque liquid scintillator detector doped with Indium with a ^{51}Cr neutrino source placed in the center.

APPENDIX B: NEUTRINO CAPTION CROSS SECTION

For future studies, we provide the neutrino capture cross section on ^{115}In in Fig. 5 as a function of incoming neutrino energy E_ν . The $^{115}\text{Sn}^*$ nucleus is produced in the $7/2^+$ excited state, corresponding to a Gamow-Teller transition. Therefore, the cross section for neutrino capture on indium is [15,39]

$$\sigma_{\text{In}}(E_\nu) = \frac{2\pi^2 \ln 2}{m_e^3} \frac{1}{(ft)_{\text{inv}\beta}} W_e p_e \mathbf{F}(Z, W_e), \quad (\text{B1})$$

where $(ft)_{\text{inv}\beta} = 2.5 \times 10^4 \text{ s}$, $W_e = (\frac{E_\nu - Q + m_e}{m_e})$ is the total electron energy including the rest mass (in m_e units), $p_e = \sqrt{W_e^2 - 1}$ is electron momentum (in m_e units), $Q = 114 \text{ keV}$ is the threshold energy, and correction from the emitted electron in the nuclear Coulomb field $\mathbf{F}(Z, W_e)$ is the Fermi function given by

$$\mathbf{F}(Z, W_e) = 2(1 + \gamma)(2p_e R)^{2(\gamma-1)} \times \text{Exp}\left(\pi\alpha Z \frac{W_e}{p_e}\right) \times \frac{|\Gamma(\gamma + i\alpha Z \frac{W_e}{p_e})|^2}{\Gamma(2\gamma + 1)},$$

where $\gamma = (1 - \alpha^2 Z^2)^{1/2}$, $R = \frac{1}{2}\alpha A^{1/3}$, α is fine-structure constant, $Z = 50$ is the atomic number, and $A = 115$ is the mass number. Note that we have adopted the same value of the $(ft)_{\text{inv}\beta}$ as argued and quoted in Ref. [15].

APPENDIX C: EVENT RATE EXPRESSIONS

The differential electron recoil spectrum from neutrino capture in an In-doped LiquidO type detector with ^7Be solar neutrino flux and ^{51}Cr source respectively, is calculated as follows:

$$\begin{aligned} \left(\frac{d^2 N_\nu}{dr dE_R}\right)_{^{51}\text{Cr}} &= \frac{M_{\text{Ind}}}{A_{\text{Ind}} m_u V_{\text{det}}} \left(\frac{1 - e^{-\lambda T_{\text{obs}}}}{\lambda}\right) \\ &\times \sum_{j=1}^{\text{all Cr } \nu\text{-lines}} N_{\nu,j}^{\text{Cr}} \sigma_{\text{In}}(E_{\nu,j}) \\ &\times P_{ee}^{\text{MSW}}(E_{\nu,j}, r) \mathcal{R}(E_{\nu,j}, E_R) \end{aligned} \quad (\text{C1})$$

$$\begin{aligned} \left(\frac{d^2 N_\nu}{dr dE_R}\right)_{^7\text{Be}} &= \frac{4\pi M_{\text{Ind}}}{A_{\text{Ind}} m_u V_{\text{det}}} T_{\text{obs}} r^2 \\ &\times \sum_{\text{both } ^7\text{Be } \nu\text{-lines}} \sigma_{\text{In}}(E_\nu) P_{ee}^{\text{MSW}}(E_\nu) \\ &\times \Phi_{^7\text{Be}}(E_\nu) \mathcal{R}(E_\nu, E_R), \end{aligned} \quad (\text{C2})$$

where $\lambda = \ln 2 / T_{1/2}$, $T_{1/2}$ is the ^{51}Cr half-life, total observation time per source run $T_{\text{obs}} = 200 \text{ days}$, M_{Ind} is the total indium mass, $A_{\text{Ind}} = 115$, m_u is average nucleon mass, V_{det} is the total detector mass, $N_{\nu,j}^{\text{Cr}}$ is the source neutrino rate for $E_{\nu,j}$ ν line, $\Phi_{^7\text{Be}}$ is ^7Be solar ν flux, r is the radial distance from the center of the detector, E_ν is the incoming neutrino energy, E_R is the reconstructed neutrino energy (electron recoil energy being $E_R - Q$), and the energy reconstruction function $\mathcal{R}(E_\nu, E_R)$ is assumed to be Gaussian [40] with a width $\sigma_E = 5\% / \sqrt{E_R} (\text{in MeV})$ (400 photoelectrons per MeV) [16]. Since the fiber spacing ($\sim 2\text{--}3 \text{ mm}$) is much smaller than the minimum oscillation length relevant for our analysis ($\sim 10 \text{ cm}$), spatial variations in detector properties at the fiber scale are not expected to affect the results.

In Fig. 6, we show the oscillation probability P_{ee} as a function of length L and neutrino energy E_ν for four different benchmark points. Note that B1 is the benchmark point chosen in ref. [10] to explain GA. However, we find that while the energy dependence of the resonance at B1

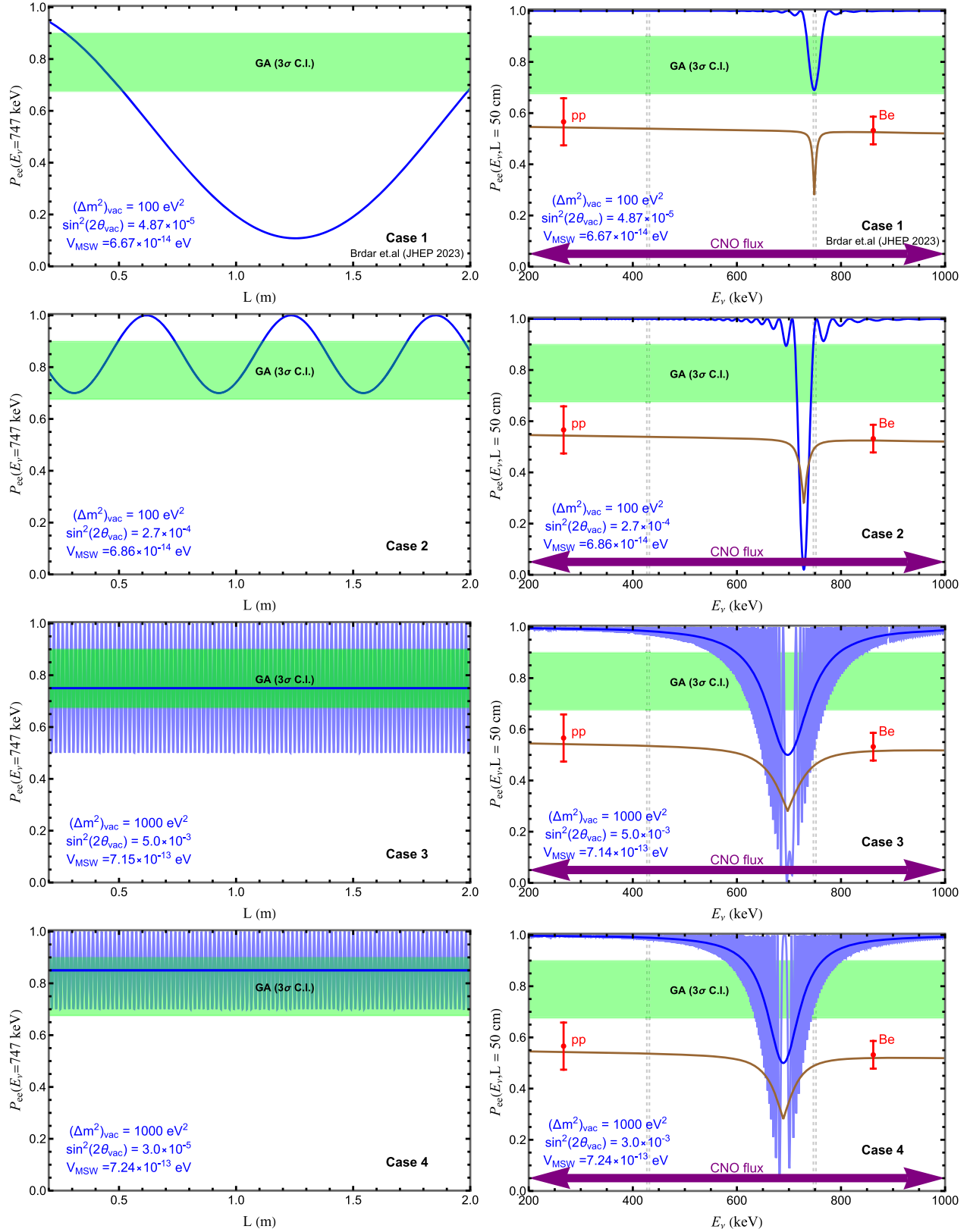


FIG. 6. The oscillation probability P_{ee} as a function of length L and neutrino energy E_ν for four different cases. Note B1 is the benchmark in Ref. [10]. In effective parameter space, these cases correspond to $(\sin^2 2\theta_{e4}^{\text{eff}}, \Delta m_{\text{eff}}^2)$: B1 (0.89, 0.74), B2 (0.3, 3), B3 (0.5, 100), B4 (0.3, 100).

agrees with the observed data, B1 lies significantly far away from the 3σ allowed region from the best-fit of all GA experiments [4]. We calculate and display the event rates in Fig. 7 for these four cases as a function of electron energy ($E_\nu - Q$) and distance from ^{51}Cr source placed inside an indium doped LiquidO setup. The above calculation assumes a single 3.4 MCi ^{51}Cr source run of about 200 days. We also show a schematic diagram for the experimental setup proposed in our work in right panel of Fig. 5. The

^{51}Cr neutrino source is placed in the center of the segmented opaque liquid scintillator detector doped with indium.

APPENDIX D: χ^2 -DEFINITION

We choose to define the χ^2 in terms of number of events in each radial bin and for two energy bins for E_R above and below 534 keV, labeled $N_{i,750}^{\text{dip/SM}}$ and $N_{i,430}^{\text{dip/SM}}$, respectively,

$$\begin{aligned} \chi^2(\vec{\xi}) = & \sum_{i=1}^{\text{all r bins}} 2 \left[\left(N_{i,430}^{\text{SM}}(\vec{\xi}) - N_{i,430}^{\text{dip}} \right) + N_{i,430}^{\text{dip}} \ln \left(\frac{N_{i,430}^{\text{dip}}}{N_{i,430}^{\text{SM}}(\vec{\xi})} \right) + \left(N_{i,750}^{\text{SM}}(\vec{\xi}) - N_{i,750}^{\text{dip}} \right) + N_{i,750}^{\text{dip}} \ln \left(\frac{N_{i,750}^{\text{dip}}}{N_{i,750}^{\text{SM}}(\vec{\xi})} \right) \right] \\ & + \left(\frac{\xi_{\text{CrFlux}}^{430}}{\sigma_{\text{CrFlux}}^{430}} \right)^2 + \left(\frac{\xi_{\text{BeFlux}}}{\sigma_{\text{BeFlux}}} \right)^2 + \left(\frac{\xi_{\sigma\text{In}}}{\sigma_{\sigma\text{In}}} \right)^2 + \left(\frac{\xi_{\text{BR}}}{\sigma_{\text{BR}}} \right)^2 \\ N_{i,430}^{\text{SM}}(\vec{\xi}) = & (1 + \xi_{\text{CrFlux}}^{430})(1 + \xi_{\sigma\text{In}}) \cdot N_{i,\text{Cr},\text{low}}^0 \\ \simeq & (1 + \xi_{\sigma\text{In}} + \xi_{\text{CrFlux}}^{430}) \cdot N_{i,\text{Cr},\text{low}}^0 \\ N_{i,750}^{\text{SM}}(\vec{\xi}) = & (1 + \xi_{\sigma\text{In}}) \left[\left(1 - \frac{\xi_{\text{BR}} B_L^0}{(1 - B_L^0)} \right) \frac{(1 + \xi_{\text{CrFlux}}^{430})}{(1 + \xi_{\text{BR}})} \cdot N_{i,\text{Cr},\text{high}}^0 + (1 + \xi_{\text{BeFlux}}) \cdot N_{i,\text{Be}7}^0 \right] \\ \simeq & \left(1 - \frac{\xi_{\text{BR}}}{B_H^0} + \xi_{\text{CrFlux}}^{430} + \xi_{\sigma\text{In}} \right) \cdot N_{i,\text{Cr},\text{high}}^0 + (1 + \xi_{\text{BeFlux}} + \xi_{\sigma\text{In}}) \cdot N_{i,\text{Be}7}^0, \end{aligned}$$

where $N_{i,\text{Cr},\text{high/low}}^0$ are the standard expected rates with branching ratios set to central values $B_{H/L}^0$. The $(\xi_{\text{CrFlux}}, \xi_{\text{BeFlux}}, \xi_{\sigma\text{In}}, \xi_{\text{BR}})$ are the pull terms for ^{51}Cr flux normalization at 430 keV neutrino lines ($\sigma_{\text{CrFlux}}^{430} \sim 0.234\%$) [27,41], Be flux normalization ($\sigma_{\text{BeFlux}} \sim 2.6\%$) [33], indium neutrino capture cross section ($\sigma_{\sigma\text{In}}$) and the branching ratio for the Cr neutrino lines to 430 keV lines ($\sigma_{\text{BR}}^{430} \sim 0.5\%$) [42–45]. Note that the calorimetric measurement only depends primarily on 320 keV gamma ray; therefore, it technically determines the total activity for the 427 and 432 keV neutrino lines within $\sigma_{\text{CrFlux}}^{430} \sim 0.234\%$. Here, N_i^{SM} is the expected event rate in the standard case, N_i^{dip} is the event rate with the MSW resonance. We scan over a given indium mass $M_{\text{Ind}} \simeq \{0.3, 1.2, 2, 5, 11, 16, 20, 27, 33, 50, 101\}$ tons assuming a 20% loading by weight and obtain an optimum M_{Ind} for each point in the parameter space for which the sensitivity exceeds 5σ , with results shown in Fig. 3.

In Fig. 8, we uniformly scan over the allowed parameter space of the ν_s -DM MSW resonance model and indicate the indium mass required to reach a confidence interval (CI) of greater than 5σ (colored points except black), with the Indoped LiquidO setup. The black points correspond to point in the parameter space for which the significance remains less than 5σ despite a large indium mass. The upper panels are results for single source runs with a floating precision on indium cross-section in the left panel and a 2.6% precision in the right panel. The lower panels correspond to second and third source run for the 2.6% precision case. It can be clearly seen that the ν_s -DM MSW resonance model can be completely probed at 5σ level if the $\sigma_{\sigma\text{In}} \leq 2.6\%$.

For completeness, we similarly show the sensitivity of the above setup to the vanilla eV-scale sterile neutrino scenario in Fig. 9, although this model is highly disfavored from multiple different experiments (solar, reactor, cosmological).

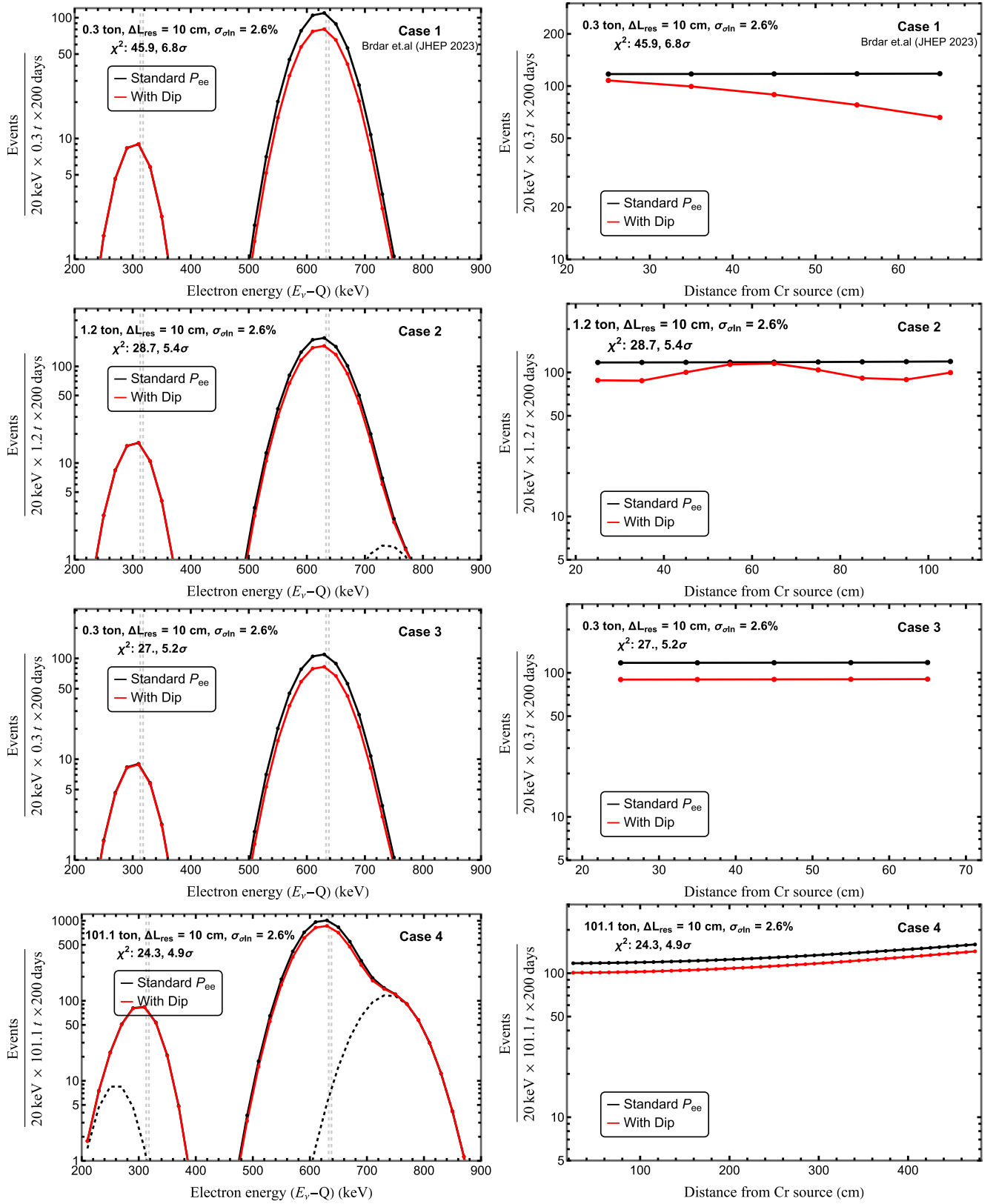


FIG. 7. Event rates as a function of electron energy ($E_\nu - Q$) and distance from ^{51}Cr source in an indium doped LiquidO style detector for a single source run of about 200 days, for the four benchmark points in Fig. 6.

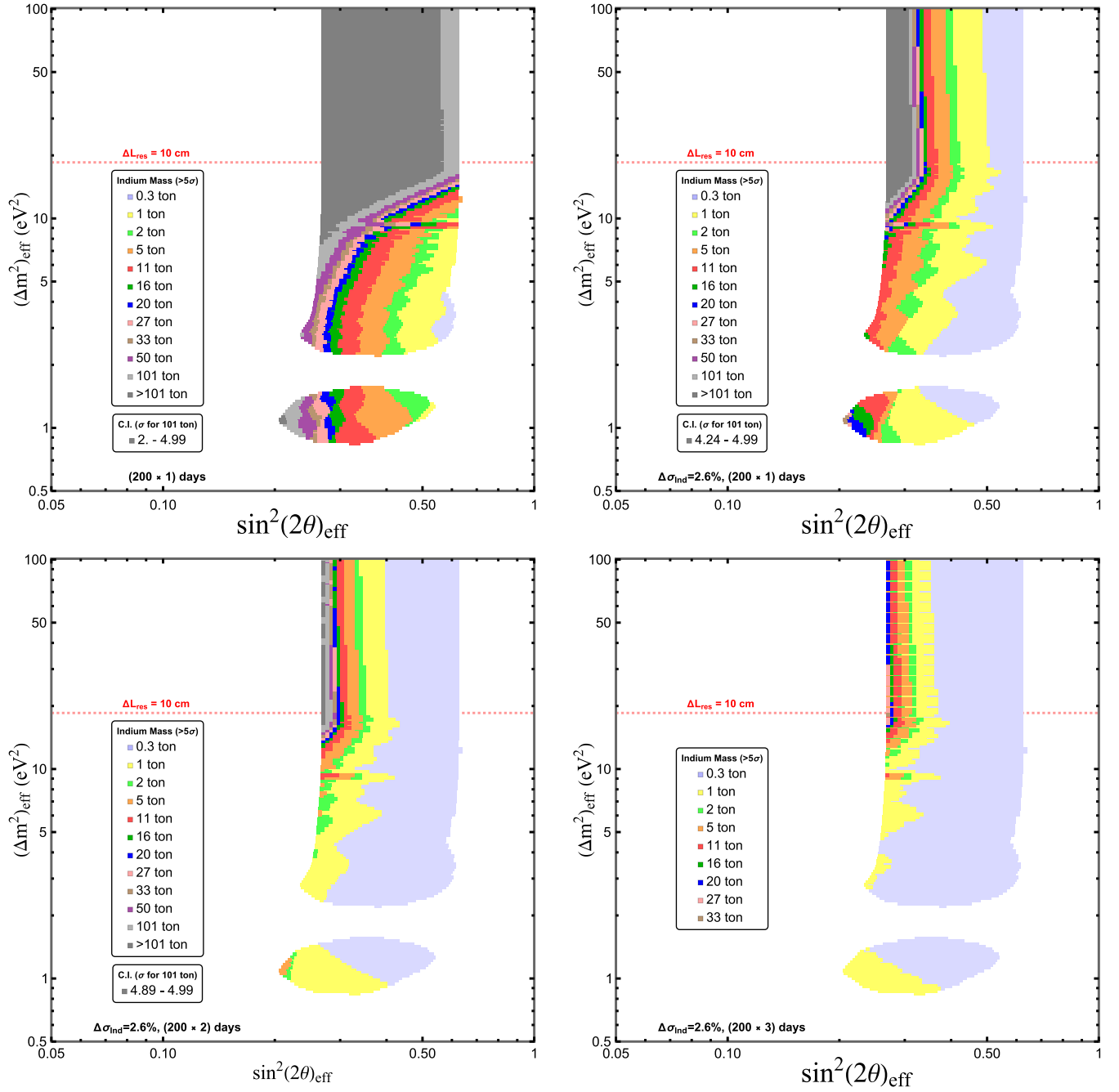


FIG. 8. Plots for sensitivity of the In-doped LiquidO setup to effective parameter space of the ν_s -DM MSW resonance model. The colored points indicate the indium mass required to reach a confidence interval (CI) of greater than 5σ , except the black points for which the significance is less than 5σ . All the points shown here are sampled uniformly from the allowed parameter space. The upper panels are results for single source runs with a floating precision on indium cross-section in the left panel and a 2.6% precision in the right panel. The lower panels correspond to second and third source run for the 2.6% precision case.

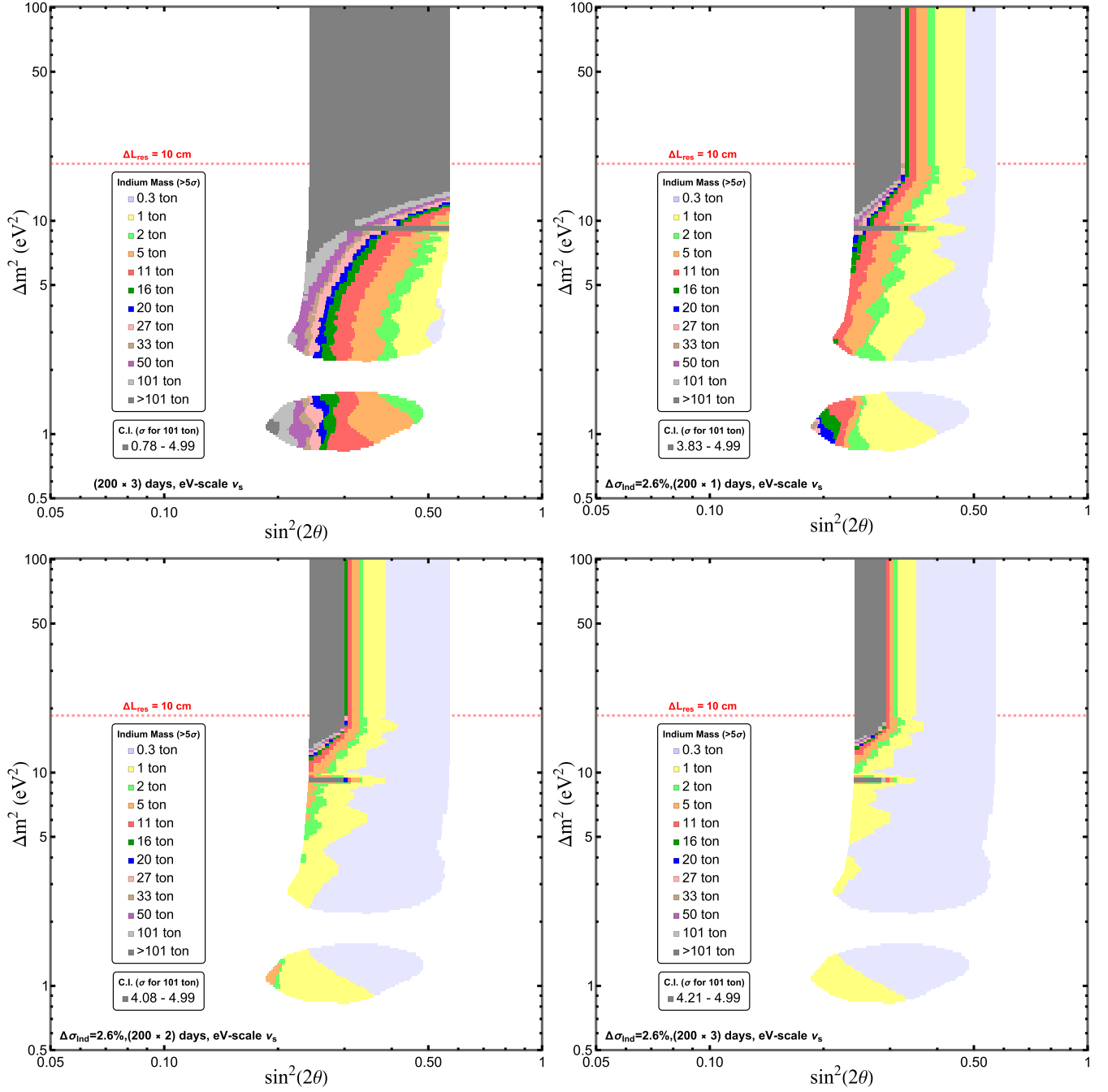


FIG. 9. Plots for sensitivity of the In-doped LiquidO setup to the vanilla eV-scale sterile neutrino scenario. The colored points indicate the indium mass required to reach a confidence interval (CI) of greater than 5σ , except the black points for which the significance is less than 5σ . All the points shown here are sampled uniformly from the allowed parameter space. The upper panels are results for single source runs with a floating precision on indium cross section in the left panel and a 2.6% precision in the right panel. The lower panels correspond to second and third source run for the 2.6% precision case.

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